

MOND and the “Dearth of Dark Matter in Ordinary Elliptical Galaxies”

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ABSTRACT

The recent findings of Romanowsky et al., of an “unexpectedly” small mass discrepancy within 5 effective radii in several elliptical galaxies, are not surprising in the context of MOND. As we show here, they are, in fact, in full concordance with its predictions. One is dealing with high-surface-density galaxies with mean accelerations rather larger than the acceleration constant of MOND. These findings continue, and are now the extreme examples of, the trend predicted by MOND: the mass discrepancy sets in at larger and larger scaled radii in galaxies with larger and larger mean surface densities; or, equivalently, mean accelerations.

Subject headings: dark matter galaxies: kinematics and dynamics

1. Introduction

Romanowsky et al. (2003) have recently presented dynamical studies of three elliptical galaxies based on the measurement of radial velocities of a large number of planetary nebulae in each of these galaxies. This method is rather more reliable, and is extended to considerably larger radii, than the standard method of interpreting the line-of-sight-integrated line profiles (see e.g., Gerhard et al. 2001, and Baes and Dejonghe 2002). The dynamical modelling of Romanowsky et al. (2003) “indicates the presence of little if any dark matter in these galaxies”. They conclude that this does not naturally conform with the CDM paradigm.

Our purpose is to point out that the results of Romanowsky et al. are not only in agreement with the predictions of MOND, but go beyond existing support of MOND, probing, as they do, the highest acceleration end in the galaxy sequence, higher than what has been probed with rotation curves of spiral galaxies.

MOND is an empirically motivated modification of Newtonian dynamics at low accelerations, suggested as an alternative to dark matter (Milgrom 1983). For quasi-spherical

galaxies such as we have at hand here, the true (MOND) acceleration \mathbf{g} is, to a very good approximation, related algebraically to the acceleration \mathbf{g}_n calculated from Newtonian dynamics via

$$\mathbf{g}\mu(|\mathbf{g}|/a_0) = \mathbf{g}_n,$$

where a_0 is the MOND acceleration constant, and the interpolating function $\mu(x)$ approaches 1 in the limit $x \gg 1$ (the Newtonian limit), and approaches x at low accelerations $x \ll 1$ (the MOND limit). Thus, in this low acceleration limit $g = \sqrt{g_n a_0}$, predicting asymptotically flat rotation curves for finite mass bodies, with an asymptotic velocity of $V_\infty = (GMa_0)^{1/4}$, where M is the total (baryonic) mass.

Newtonian dynamics predicts, of course, that masses having homologous density distributions will have similar rotation curves. This is not so in MOND, where the existence of a preferred acceleration value implies different behavior for galaxies with different surface densities relative to the critical value $\Sigma_m = a_0/G$. In other words, the MOND potential field, and, in particular, the shape of the MOND rotation curve, depends on the parameter (Milgrom 1983)

$$\xi \equiv (MG/R_e^2 a_0)^{1/2} = V_\infty^2/R_e a_0,$$

where R_e is some measure of the size of the (baryonic) galaxy, which for ellipticals we take as the effective radius (the projected half-mass radius).

Galaxy systems with $\xi \gg 1$ have internal accelerations greater than a_0 in their main body, which is thus in the Newtonian regime. Such high-surface-density objects are expected to show only a mild mass discrepancy within a few R_e , as, in this case, ξR_e marks the transition radius from the Newtonian to the MOND regime. At the other end, low surface density galaxies, with $\xi \ll 1$, are in the MOND regime throughout, and are predicted to show a large mass discrepancy within the optical image.

As a class, normal elliptical galaxies lie at the high ξ end of this sequence. Assuming a mean $M/L = 4$ for the elliptical galaxies observed and catalogued by Jørgensen et al. (1995a,b), we estimate that $\langle \xi \rangle = 3.5$ for this sample, compared to values of typically 2 to 3 for HSB disk galaxies.

In light of all this, the results of Romanowsky et al. (2003) are expected in MOND.

In section 2 we compare these results with the predictions of MOND, and discuss the implications in section 3.

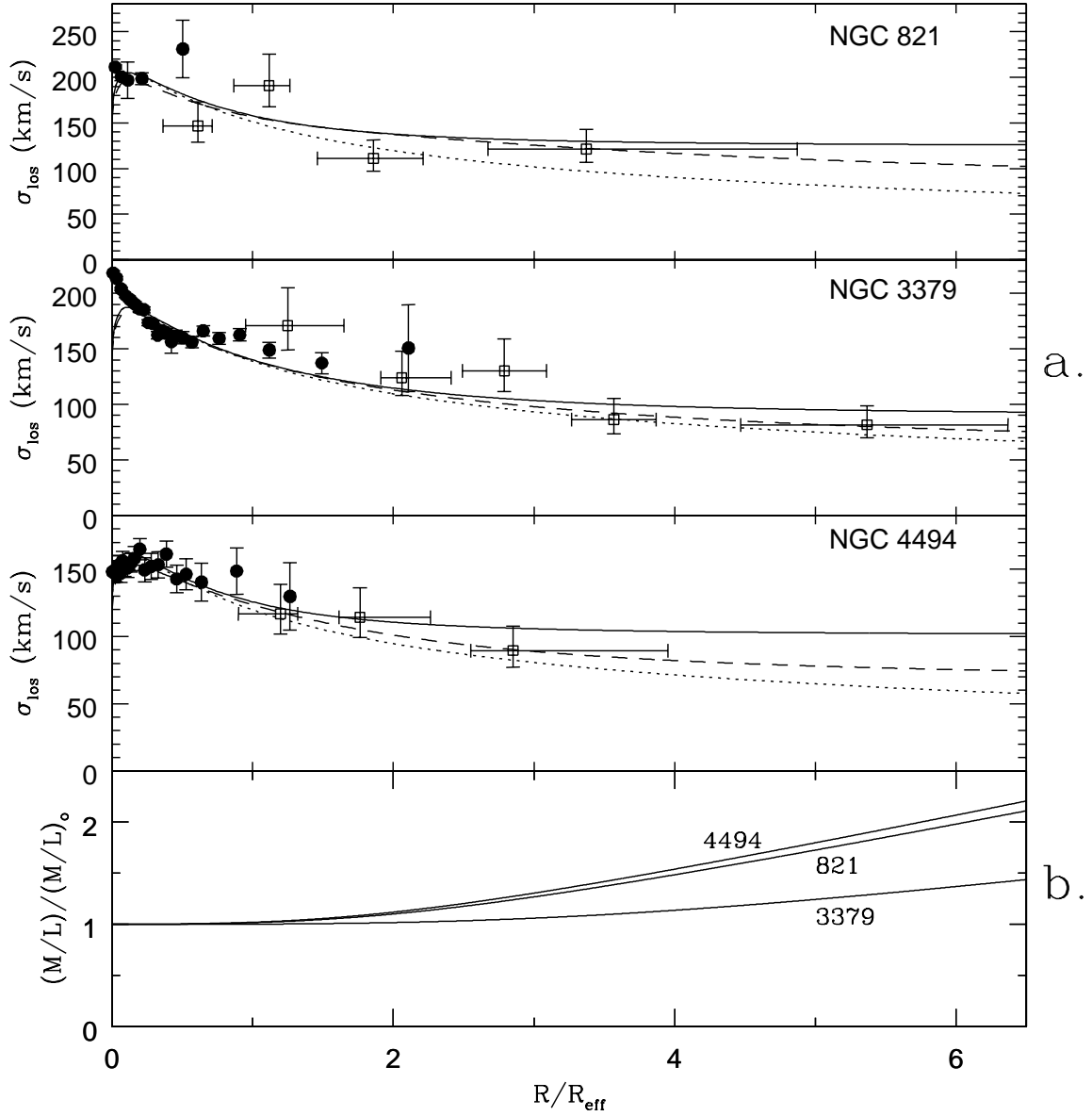


Fig. 1.— a.) The top three panels show the line-of-sight velocity dispersion for the three elliptical galaxies observed by Romanowsky et al. as a function of radius in units of the effective radius. The solid points are earlier observations of the stellar velocity dispersion and the open squares are the PN observations. The dotted line is the predicted, Newtonian, line-of-sight velocity dispersion for isotropic, constant M/L models. The solid lines are the MOND predictions for the same models. The dashed lines are the MOND predictions for models with a variable anisotropy ratio, as described in the text. b.) The lower panel shows the MOND prediction for the Newtonically deduced runs of M/L (normalized to the central value).

2. Results

The essential results of Romanowsky et al. (2003) are reproduced in our Fig. 1a, which is based on their Fig. 4. The points with error bars show the velocity dispersion of planetary nebulae averaged over the indicated radial bins as a function of radius in units of the effective radius. The solid points are measurements of the stellar velocity dispersion. We see that the planetary nebulae kinematics probe the gravitational field to considerably larger radii than do the stellar kinematics, particularly in the case of NGC 3379. The dotted line, also from Fig. 4 of Romanowsky et al., shows the predicted line-of-sight velocity dispersion assuming that light traces mass and that the velocity distribution is isotropic. The light distribution is fitted with a Hernquist model (Hernquist 1990) having the appropriately chosen effective radius. The corresponding B-band mass-to-light ratios are, in solar units, 11.4 for NGC 821, 4.7 for NGC 3379, and 5.4 for NGC 4494. The obvious conclusion is that, except perhaps for NGC 821, the observations are consistent with these light-traces-mass models and the required M/L values suggest little dark matter, if any. A fourth galaxy, NGC 4697, was studied earlier (Méendez et al. 2001). It was probed to smaller radii, and seems to indicate similar behavior. We will only discuss it in passing.

We also show in Fig. 1a the predictions of MOND, with the solid lines corresponding to the same Hernquist models and to isotropic velocity distributions. The MOND interpolating function is taken to have the same form always used before in rotation curve studies, i.e.,

$$\mu(x) = x/\sqrt{1+x^2},$$

and we use a value of $a_0 = 1 \times 10^{-8} \text{ cm s}^{-2}$, based upon the analysis of Bottema et al. (2002) making use of the new distance scale. (All along we use the distances adopted by Romanowsky et al.; recall that the distance affects the MOND predictions differently from those of Newtonian dynamics.)

There is, of course, nothing preferable about an isotropic velocity distribution; so, to gain some idea of the uncertainty due the unknown orbit population, we also show MOND models with a variable anisotropy ratio (becoming more radial outwards). The anisotropy parameter in these models is given by

$$\beta = \frac{r^2}{(r_a^2 + r^2)}$$

where the anisotropy radius $r_a = 3R_e$ in all cases. Such a run of anisotropy is typical of systems that form by dissipationless collapse (van Albada 1982).

Fig. 1b shows the MOND predicted M/L runs, normalized to the central value, for the three galaxies (calculated solely from the light distribution, and simply given by $1/\mu(|\mathbf{g}|/a_0)$).

They give the predicted runs of Newtonically deduced mass discrepancy. So, MOND does predict a mild mass discrepancy in these three galaxy within the range studied. Romanowsky (private communication) finds that the range of M/L values deduced from Jeans modelling of the velocity data of NGC 821 and NGC 4494, *considering only models with a constant anisotropy ratio*, are milder than those given in Fig. 1b. The differences are, however, well within the uncertainties due to measurement errors, assumed distances, and modelling.

We see that, by and large, the binned, line-of-sight dispersion data are as consistent with the MOND predictions as they are with the Newtonian, no DM ones. The reason is that within the radii measured the mass discrepancy predicted by MOND is not larger than the measurement errors and/or the uncertainties due to the unknown orbit population.

To better manage these latter uncertainties, Romanowsky et al. applied to the best studied galaxy, NGC 3379, an orbit-library method described in detail in their paper (this entails, of course, variable anisotropies in the velocity distribution). The outcome of this analysis is a better constrained range of allowed potential fields for this galaxy. This is described as a permitted range of rotation curves given in their Fig A2, and reproduced here in our Fig. 2 as the hatched area. The dotted curve in Fig. 2 shows the Newtonian rotation curve for the adopted Hernquist model, with a constant M/L_B value of 5.5 solar units, chosen to fit the inner parts, near the maximum (and no dark matter). The solid line is the MOND prediction for the same mass model. The MOND rotation curve for a spherical galaxy with a de Vaucouleur profile having $\xi = 5$ is, in fact, given in Figure 1b of Milgrom (1983), and matches very nearly the deduced rotation curve for NGC 3379, which has $\xi \approx 5.7$.

We see that this more refined distillation of the data, encapsuled in the deduced rotation curve, does indicate the development of a mild mass discrepancy at the larger radii, rather as predicted by MOND. Note that because the accelerations at several effective radii are near a_0 , the exact shape of the MOND rotation curve depends upon the precise form of μ , but here this is a relatively unimportant detail. The main point is that MOND predicts the very pronounced decline in the deduced rotation curve of NGC 3379, as never seen before.

3. Discussion

We see that the MOND predictions of the kinematics of the galaxies under study, as deduced from the observed light distribution assuming a constant M/L value, agree well with the observations, assuming very reasonable orbit populations. The strength and importance of these findings is, however, not in the exact quality of the agreement. We have seen more

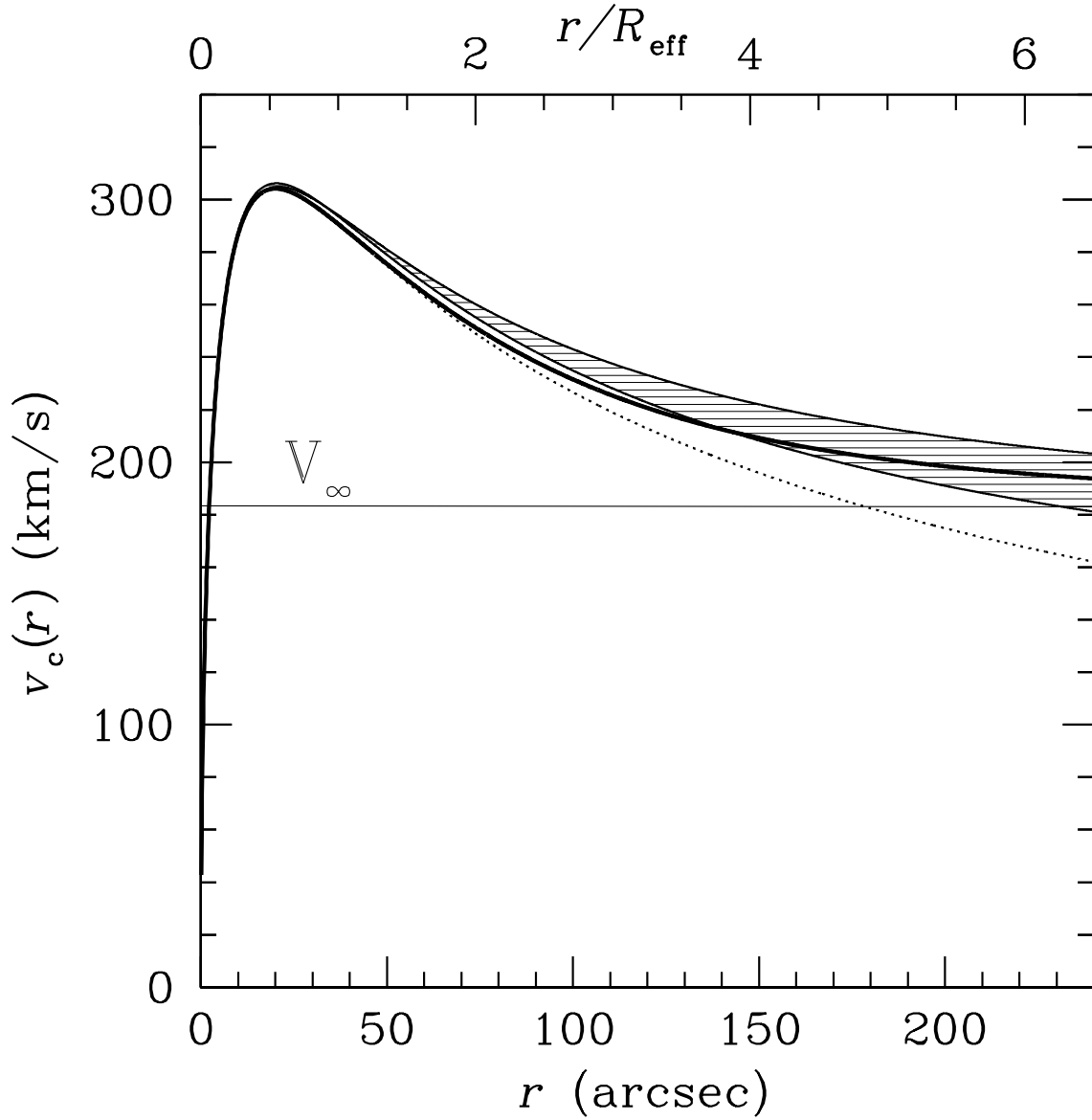


Fig. 2.— The inferred rotation curves of NGC 3379. The shaded area shows the region permitted by the orbit modelling of PN radial velocities by Romanowsky et al.. The dotted line shows the constant $M/L = 5.5$, Newtonian rotation curve inferred from the stellar light distribution. The heavy solid line is the MOND rotation curve determined from this constant M/L model. The horizontal line shows the MOND asymptotic velocity (V_∞), i.e., the circular velocity at infinity. This could be compared with the $\xi = 5$ curve in Fig. 1b of Milgrom (1983)

impressive performances of MOND in predicting rotation curves of disc galaxies (e.g., Sanders & McGaugh 2002), where the data are more accurate, and where the uncertainty in orbit population is hardly present. The importance here is that this new comparison confirms the prediction of MOND regarding the high acceleration end of the galaxy distribution (Milgrom 1983), which has not been probed before.

NGC 3379 is the best studied of the three and with the measurements going the farthest in unit of R_e . It has $\xi \approx 5.7$, and seems to be the present record holder among galaxies with measured extended rotation curves. Accordingly, in conformity with the MOND predictions, it is also the record holder in the extent of the observed decline of its rotation curve. For NGC 821 $\xi \approx 3.6$, and for NGC 4494 $\xi \approx 3.4$. For the previously studied NGC 4697, $\xi \approx 3.3$, similar to that of NGC 4494.

These last three galaxies are nearer in their ξ value to some of the HSB spirals, especially those with a substantial bulge. In comparison, a similarly defined quantity for dwarf spheroidal galaxies can be as small as $\xi \sim 0.1$. For LSB spirals $\xi \sim 0.5$, (e.g., NGC 1560) and for HSB spirals with measured extended rotation curves $\xi \sim 2.5$ (e.g., NGC 2903). In such HSB spirals we expect to find a similar “dearth of DM” if we measure their rotation curve only as far as a few half mass radii (for NGC 2903, about 3.5 kpc). Such HSB galaxies are well fit by a “maximum disk”, whereby the rotation curve in the inner regions is explained by the visible disk with a reasonable M/L ratio, implying that very little dark matter is required there. Because the rotation curves are, in fact, measured to rather larger radii, and a mass discrepancy does develop in full strength at the outskirts, we don’t view these HSB galaxies as devoid of a mass discrepancy, only as developing it at larger radii. This is also what MOND predicts for the galaxies in the present study (as shown by the M/L runs in Fig. 1b).

There are ellipticals with $\xi \sim 3$, as studied here, for which a mass discrepancy has been claimed already at smaller radii. If these are substantiated, and correctly interpreted, they would certainly argue against MOND. There are, for example, ellipticals such as M87 (e.g. Côté et al. 2001) and M49 (e.g., Côté et al. 2003) that have been dynamically studied by both globular cluster (GCs) dynamics and x-rays. They sit, however, at the center of galaxy clusters (“Virgo A” for M87, and the sub cluster “Virgo B” for M49). It is known that, in the context of MOND, there is a remaining “missing mass” problem for the central regions of clusters (see, e.g., Sanders 2003); that additional mass, perhaps undetected baryonic matter or massive neutrinos, is required to make up the MOND dynamical mass budget. The mass discrepancies deduced around such galaxies may be reflecting these known cluster discrepancies. Moreover, in the case of M49, which presumably falls in the external field of the main cluster together with “Virgo B”, there is a possibility of departure from viriality

in the globular cluster system (magnified by MOND effects). This might be suggested by two peculiarities: a. the velocity dispersion of the metal-rich GCs is significantly lower than that of the metal-poor ones although they both supposedly probe the same gravitation field. In fact, if taken in itself, the metal-rich-GC dispersion is consistent with MOND. b. the GC velocity dispersion profile adopted by Côté et al. (2003) (taken as that of the combined population) is not a continuation of the stellar dispersion profile at smaller radii, which, like that of the metal-rich GCs, does appear to decline with radius, and does not imply a mass discrepancy. In any event, the examples of M87 and M49 are not the clean cases of isolated galaxies which would comprise ideal tests of MOND.

In another instance, Gerhard et al. (2001) studied the dynamics of ellipticals by modelling the profiles of the line-of-sight-integrated lines, extending, typically, to $0.5R_e - 2R_e$. Their deduced, enclosed M/L values rise slowly with radius. The increase in M/L at the last measured point over the central value is in most cases between 10 and 50 percent, with a few going up to 80 percent. Gerhard et al. take this rise to be the onset of the mass discrepancy in these galaxies, which would thus occur at rather smaller radii than found by Romanowsky et al. (2003). Gerhard et al. do not show errors on their deduce values, but they state that “the typical uncertainty in the outermost circular velocity is $\pm(10 - 15)\%$ ”. This translates to a $\pm(20 - 30)\%$ uncertainty in M/L , rather comparable with the whole claimed effect in most cases. When plotted against the acceleration, their M/L values begin to increase at accelerations between 3 and 30 times higher than a_0 . Gerhard et al. view this as showing that the mass discrepancy in ellipticals sets in at accelerations that are an order of magnitude higher than in spirals, which, if true, would fly in the face of MOND.

We contend that these M/L increases reported by Gerhard et al., whatever they are due to, do not mark the onset of the mass discrepancy. Two of the three galaxies studied in Romanowsky et al., NGC 4494 and NGC 3379, are also in the Gerhard et al. sample. For NGC 4494, Gerhard et al. find that M/L increases already by 40 percent at their last measured point of $0.7R_e$. For NGC 3379, they deduce a rotation curve that becomes flat at about $1R_e$ and remains so to their last measured point of about $2R_e$, where their deduced M/L value has risen already to 20 percent above the central value, whereas Romanowsky et al. tell us that the rotation curve declines at least down to $6R_e$. If the results of Romanowsky et al. are valid, the M/L increases that Gerhard et al. find for these two galaxies cannot possibly mark the onset of the mass discrepancy; and this obviously casts heavy doubt on their conclusion for other galaxies. Note also that their M/L values increase much more slowly as a function of the acceleration than they do in spirals: instead of increasing as $1/a$, as predicted by MOND, and as observed, they increase by a few tens of percents over a decade in a . So, this is certainly not MOND translated to higher accelerations, or a “non-universality of a_0 ” as has been claimed.

These deduced M/L increases may result from actual increase in the stellar M/L values; or, they may be artifacts of the analysis, or due to unaccounted for systematics, as, in fact, has been proposed by Baes and Dejonghe (2002).

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REFERENCES

- Baes, M., & Dejonghe, H. 2002, MNRAS, 335, 441
- Bottema, R., Pestaña, J.L.G., Rothberg, B., & Sanders, R. H. 2002, A&A, 393, 453
- Côté, P., McLaughlin, D.E., Hanes, D.A., Bridges, T.J., Geisler, D., Merritt, D., Hesser, J.E., Harris, G.L.H., & Lee, M.G. 2001 ApJ, 559, 828
- Côté, P., McLaughlin, D.E., Cohen, J.G., & Blakeslee, J.P. 2003, ApJ, 591, 850
- Gerhard, O., Kronawitter, A., Saglia, R.P., & Bender, R. 2001, AJ, 121, 1936
- Hernquist, L. 1990, ApJ, 356, 359
- Jørgensen, I., Franx, M., & Kjaergard, P. 1995a., MNRAS, 273, 1097
- Jørgensen, I., Franx, M., & Kjaergard, P. 1995b., MNRAS, 276, 1341
- Méndez, R. H., Riffeser, A., Kudritzki, R.P., Matthias, M., Freeman, K. C., Arnaboldi, M., Capaccioli, M., & Gerhard, O. E. 2001, ApJ, 563, 135
- Milgrom, M. 1983, ApJ, 270, 371
- Romanowsky, A.J., Douglas, N.G., Arnaboldi, M., Kuijken, K., Merrifield, M.R., Napolitano, N.R., Capaccioli, M., & Freeman, K.C. 2003, Science, 301, 1696
- Sanders, R.H. 2003, MNRAS, 342, 901
- Sanders, R.H. & McGaugh, S.S. 2002, ARA&A, 40, 263
- van Albada, T.S. 1982, MNRAS, 201, 939